Status of Superconducting RF

Report to ITRP

April 5th 2004

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for the TESLA Collaboration

TESLA Challenges

- Gradient
  - For superconducting (SC) cavities
    - 1990: 5 MV/m in operating accelerators
    - 1990: First TESLA Workshop in Cornell
    - 1994: 1.3 GHz five-cell cavity achieves 25 MV/m in Cornell
    - 2000: 25 MV/m achieved routinely in nine-cell cavities at TTF
    - 2001: TESLA Technical Design Report: 800 GeV option
    - 2003: 35 MV/m achieved in several multi-cells
- Cost
  - see tomorrow´s talks and TDR
- Auxiliaries
  - Coupler
  - Active Tuner
- R1 issue for TESLA-800 in the report of International Linear Collider Technical Review Committee (ILC-TRC)

Distribution of Maximum Operational SRF Cavity Gradients in CEBAF by Type of Limitation

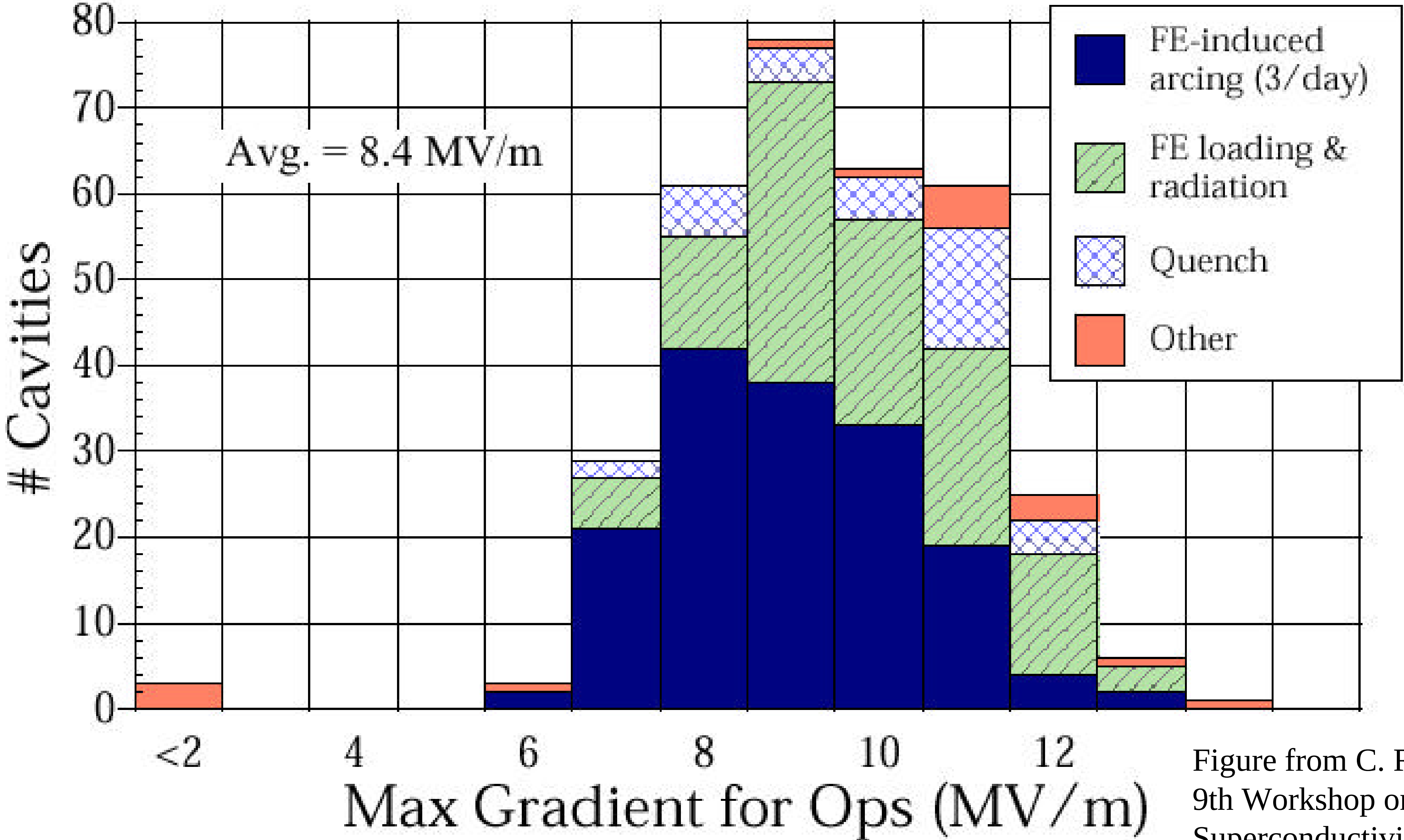
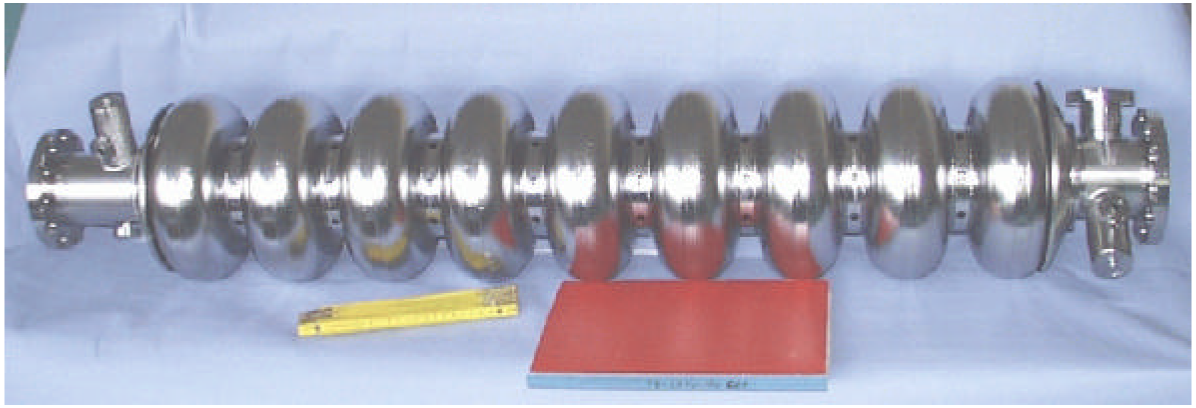


Figure from C. Reece, 9th Workshop on RF Superconductivity,1999

Superconducting Cavities

- Why?
- SC cavities offer
  - a surface resistance which is six orders of magnitude lower than normal conductors (NC)
  - high efficiency, even when cooling is included
  - low frequency, large aperture
  - high accelerating gradients
    - Theoretical limit for the TESLA shape is between 45-50 MV/m

TESLA Cavities



Made of solid, pure (RRR >300, high thermal cond.) Niobium

Nb sheets are deep-drawn to make cups (≈**100 µm tolerances**), which are electron beam welded to form structures.

Fill time with coupler 420 µs, i.e. $Q_{ext} = Q_{beam} \approx 3 \times 10^6$, ?f ≈ 400 Hz

RF pulse length (400 µs filling + 920 µs flat top) = 1320 µs.

Operated at 2 K in superfluid Helium bath.

RF losses approx. 1 W/m.

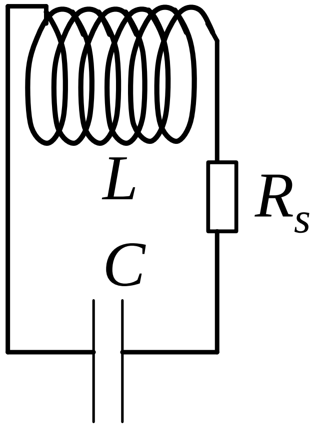
RF amplitude and phase adjusted during filling and flat top to compensate beam loading. In steady state **essentially 100% rf input power goes into the beam.**

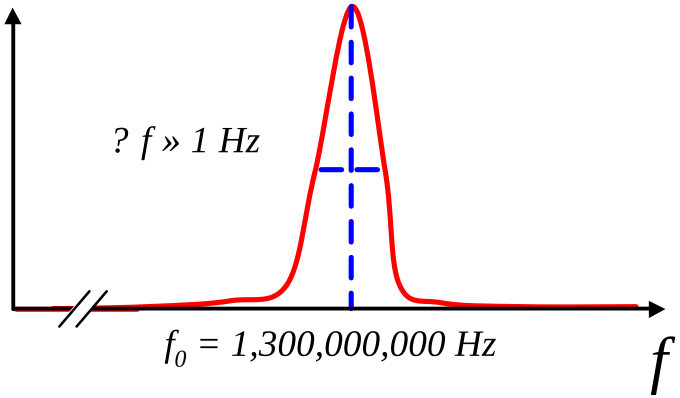
$$f_o = \frac{1}{2p\sqrt{LC}}$$

frequency

$$Q_o = \frac{f}{\Delta f} = \frac{G}{R_s}$$

quality factor

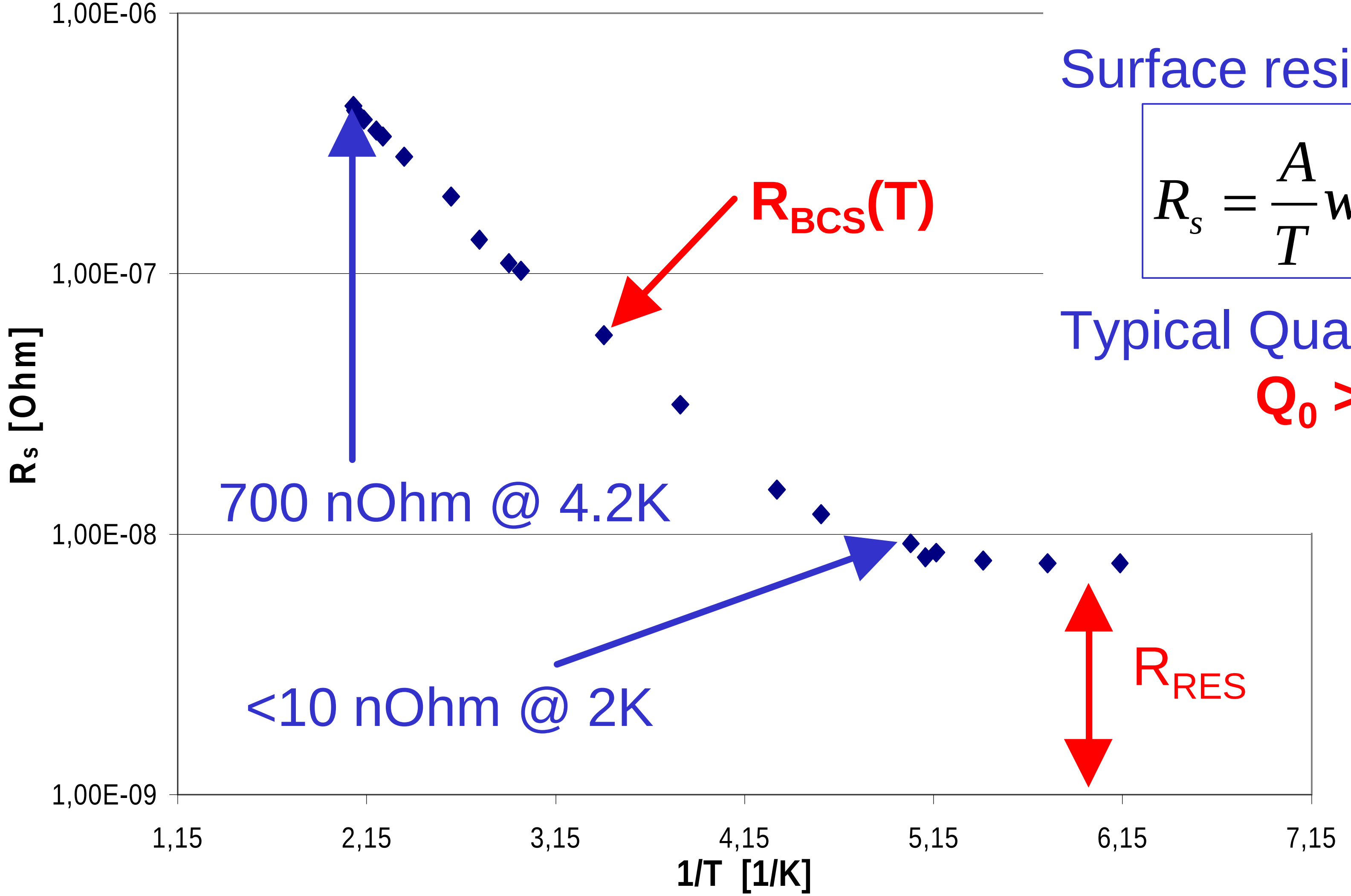




Natural bandwith

Q_0 » 10^9 -10^{10}

Surface Resistance $R_s(T)$



Geometry factor:

$$\boxed{Q_o = \frac{G}{R_s}}$$

G = 270 Ohm

Surface resistance:

$$\boxed{R_s = \frac{A}{T} w^2 e^{-\frac{\Delta}{k_B T_C}\frac{T_C}{T}} + R_{res}}$$

Typical Quality factor:

$Q_0 > 1*10^{10}$ at 2K

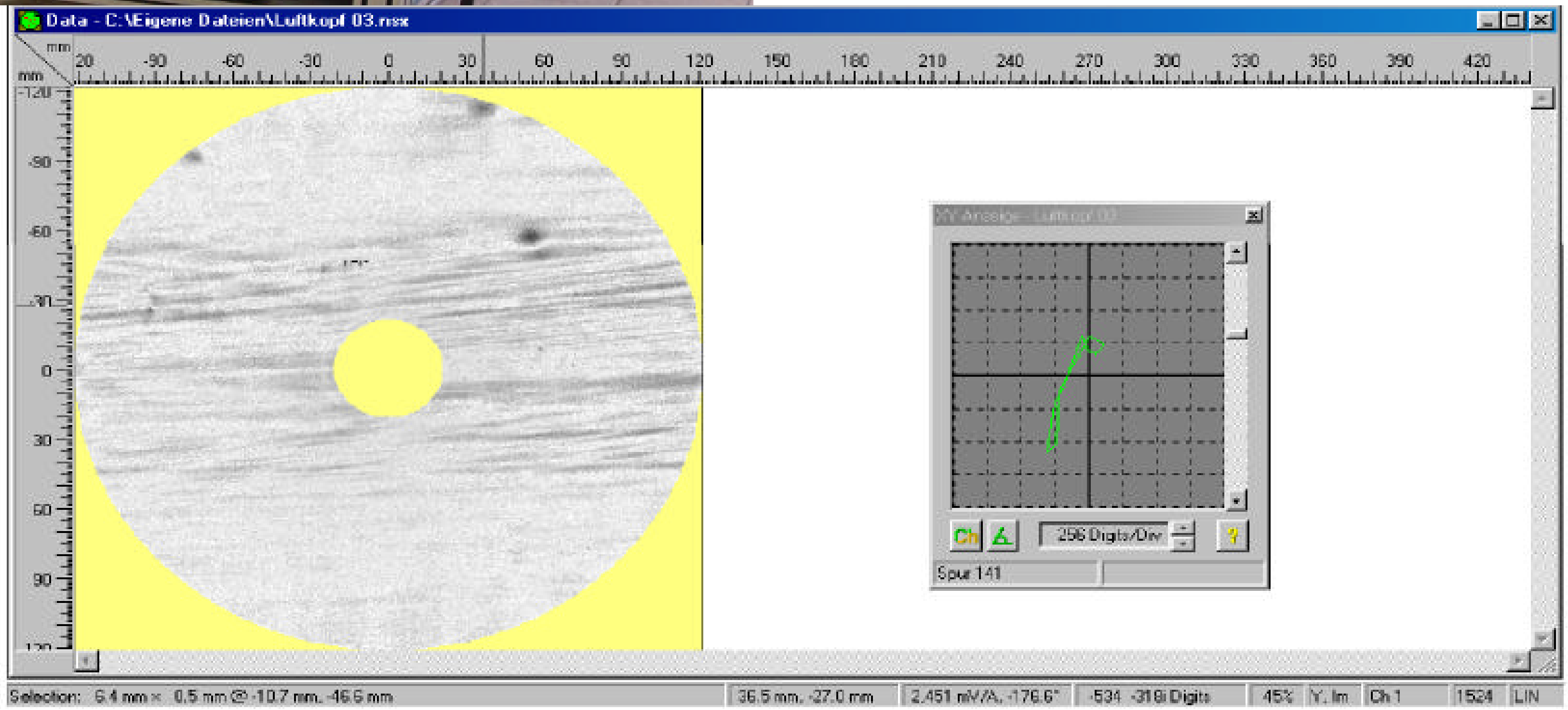
Superconducting Cavity Technology

- the small surface resistance of the superconducting necessitates avoidance of NC contaminations larger than a few µm
  - NC contaminants lead to increased power dissipation and thermal breakdown (quench)
  - as opposed to SC magnets the stored energy this is **not** a critical problem: energy in the cavities is in the order of a Joule
  - as opposed to NC structures there is **no damage** associated to thermal breakdown
- therefore
  - detailed material specification and quality control are done
    - e.g. sufficiently high thermal conductivity of the niobium
  - tight specification for fabrication e.g. welds have been implemented
  - clean room technology is a must
- all this is readily available today

Eddy Current Scanner for Niobium Sheets

Real and imaginary part of conductivity at defect, typical Fe signal

Global view, rolling marks and defect areas can be seen



Lutz

Standard Cavity Production
(e.g. EB welding at CERCA)

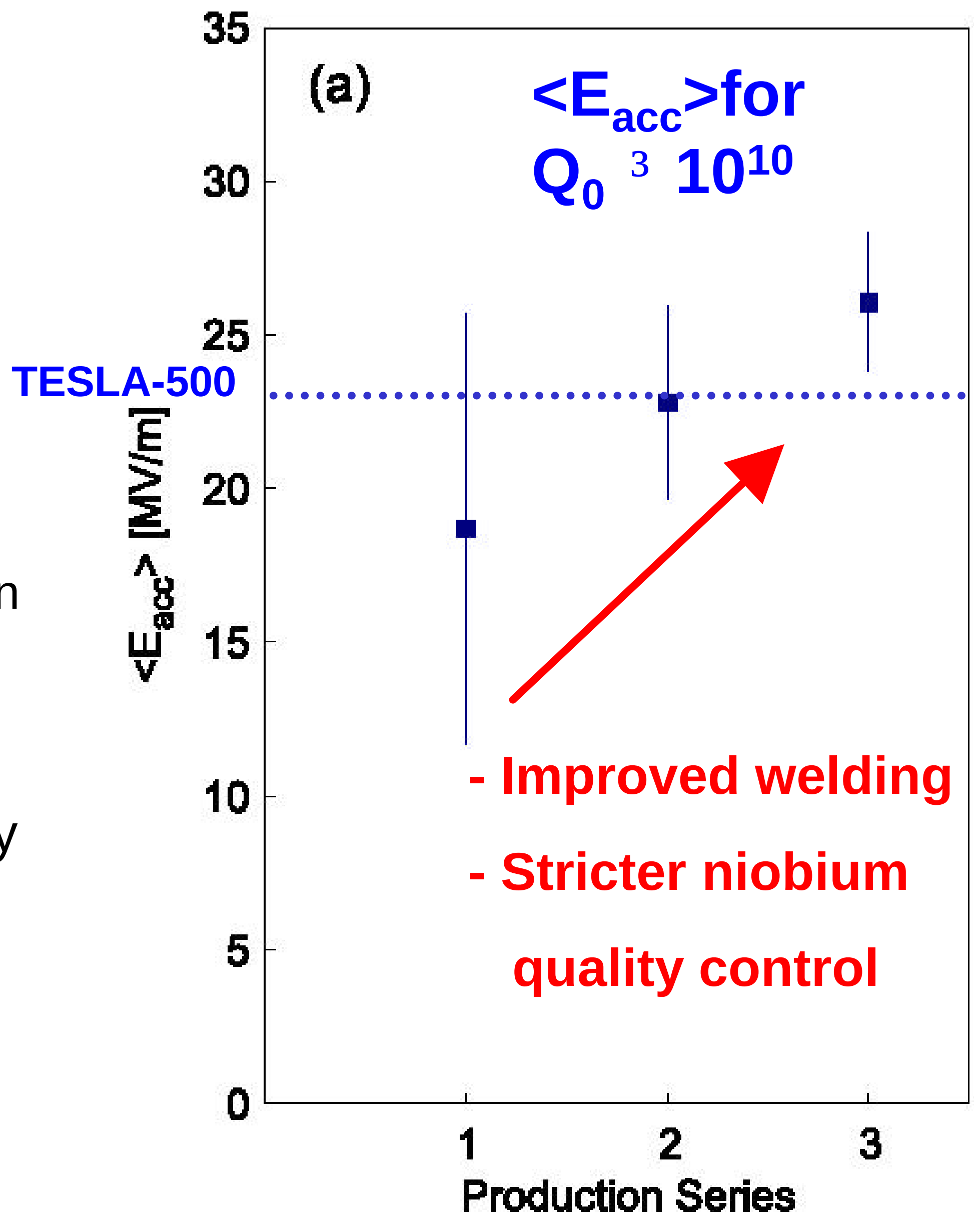
Preparation of TESLA Cavities

Preparation of TESLA Cavities

- High purity niobium sheets of Residual Resistivity Ratio RRR=300 are scanned by eddy-currents to exclude foreign material inclusions like tantalum and iron
- Industrial production of full nine-cell cavities:
  - Deep-drawing of subunits (half-cells, etc.) from niobium sheets
  - Chemical preparation for welding, cleanroom preparation
  - Electron-beam welding according to detailed specification
- 800 °C stress annealing of the full cavity removes hydrogen from the Nb
- Option: 1400 °C high temperature heat treatment with titanium getter layer to increase the thermal conductivity (RRR=500) further
- Cleanroom handling:
  - Chemical etching (or electropolishing) to remove damage layer and titanium getter layer
  - High pressure water rinsing as final treatment to avoid particle contamination

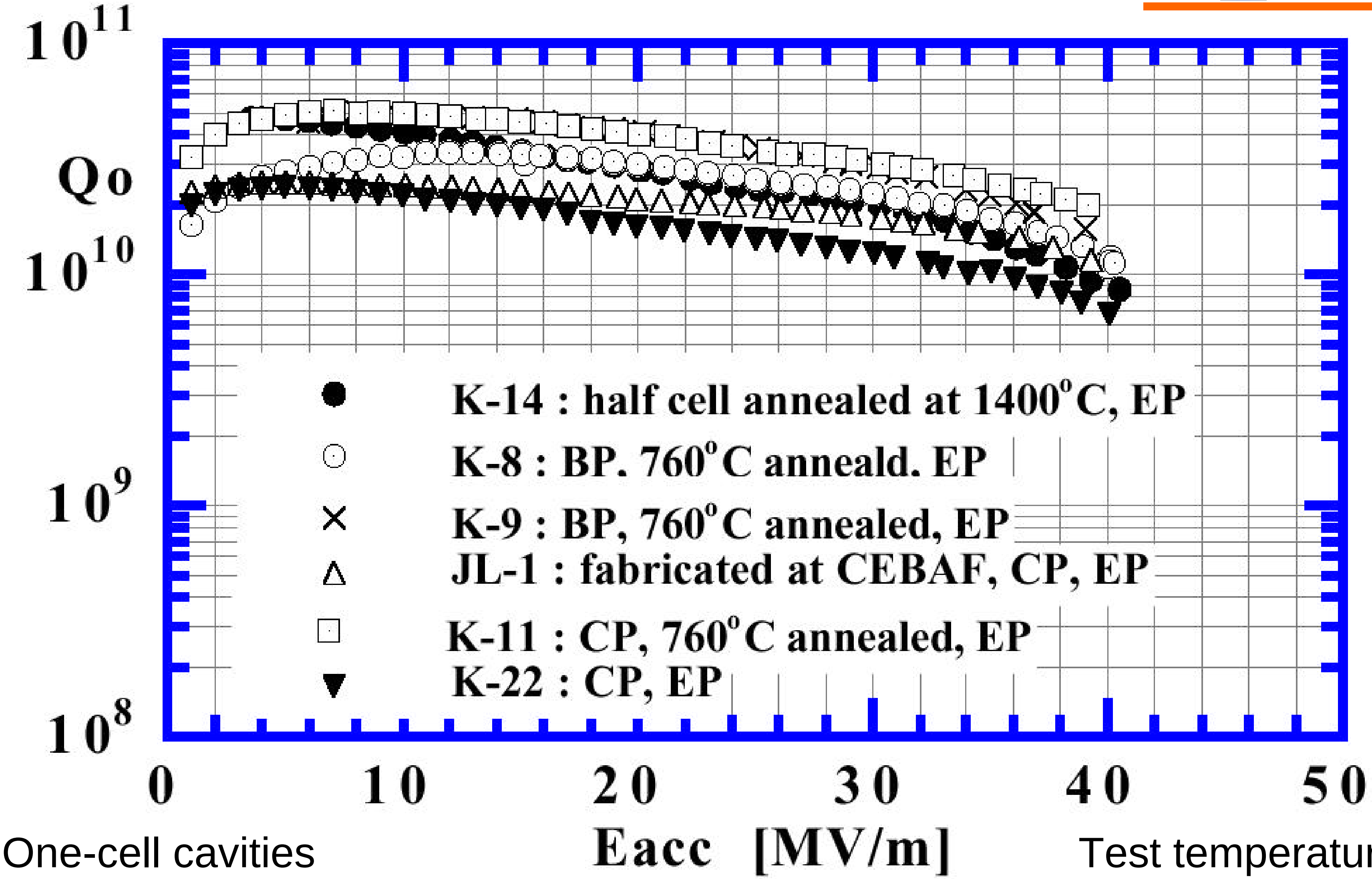
Results of Cavity Production

- Cavity shape is optimal (no change since 10 years)
- Three production series of cavities were tested to:
  - qualify companies for cavity production
  - improve performance by precise specification
- Gradient has increased to 25 MV/m in the 3rd production series of cavities by 2001 (TESLA-500 specification)
- At the same time the spread of the performance became smaller
- For TESLA-800 an improved surface treatment became available: Electropolishing (EP)



Electropolished Niobium Cavities

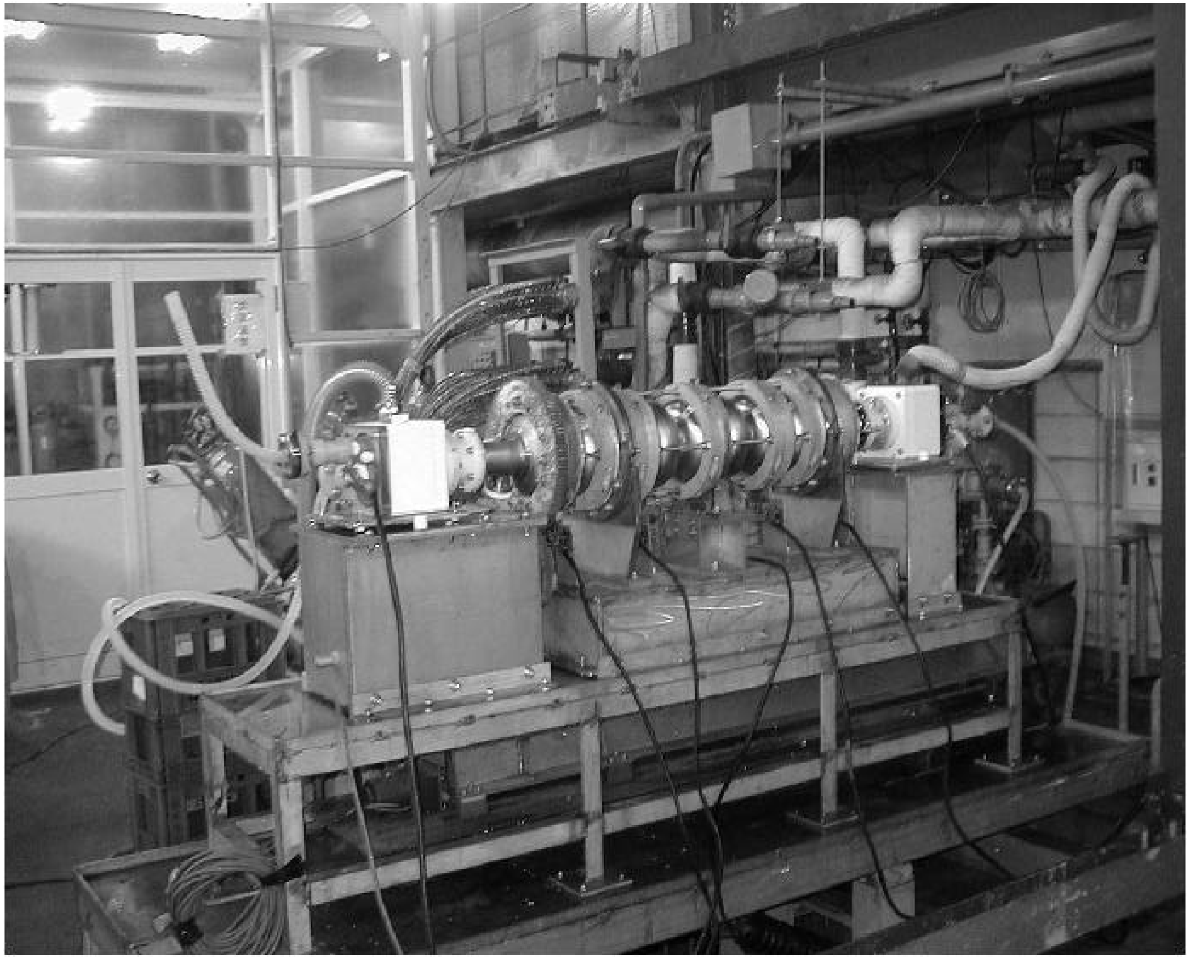
K. Saito et al. KEK 1998/1999



One-cell cavities

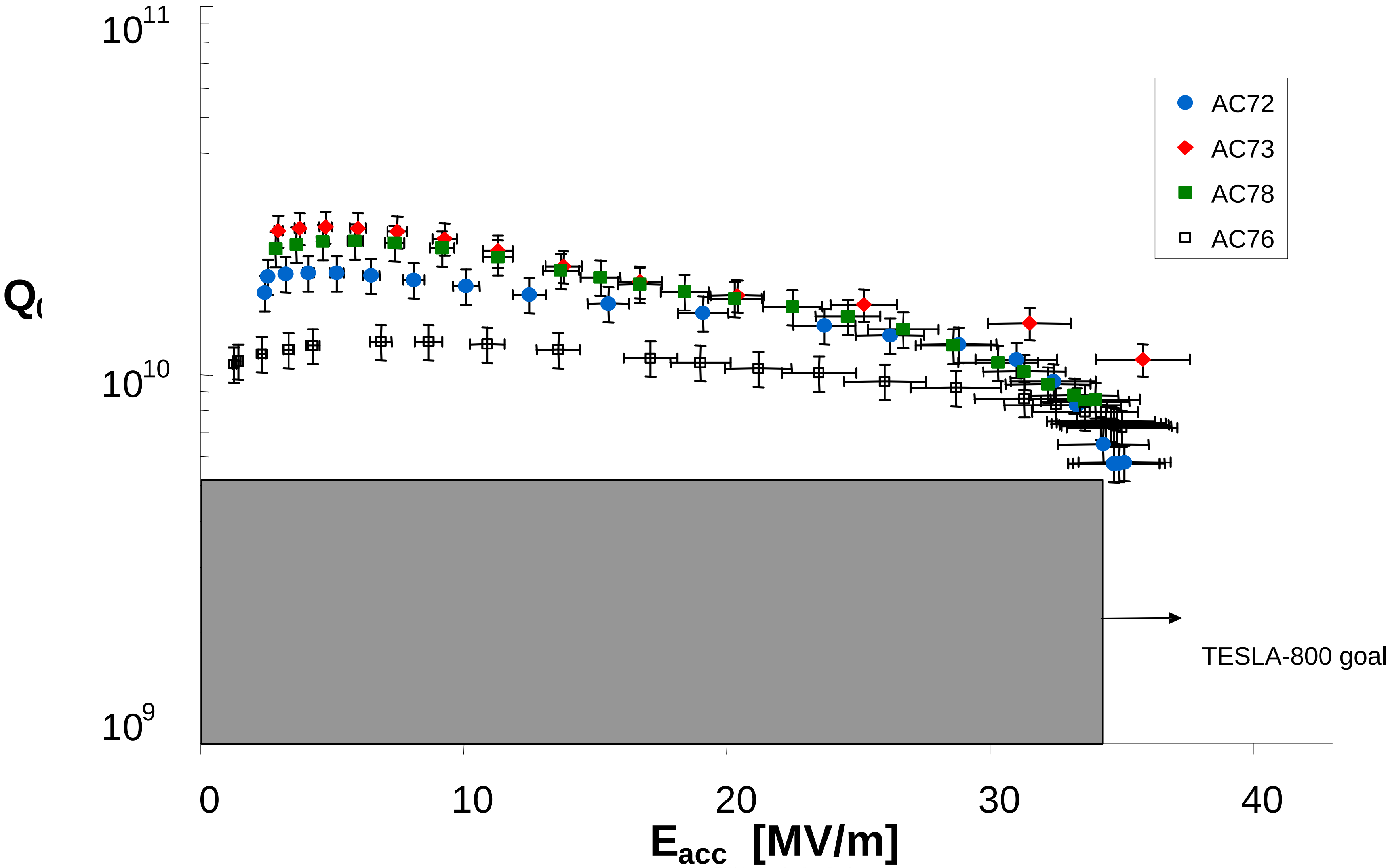
Test temperature: 1.6 K

KEK-DESY Collaboration on Electropolishing TESLA Cavities

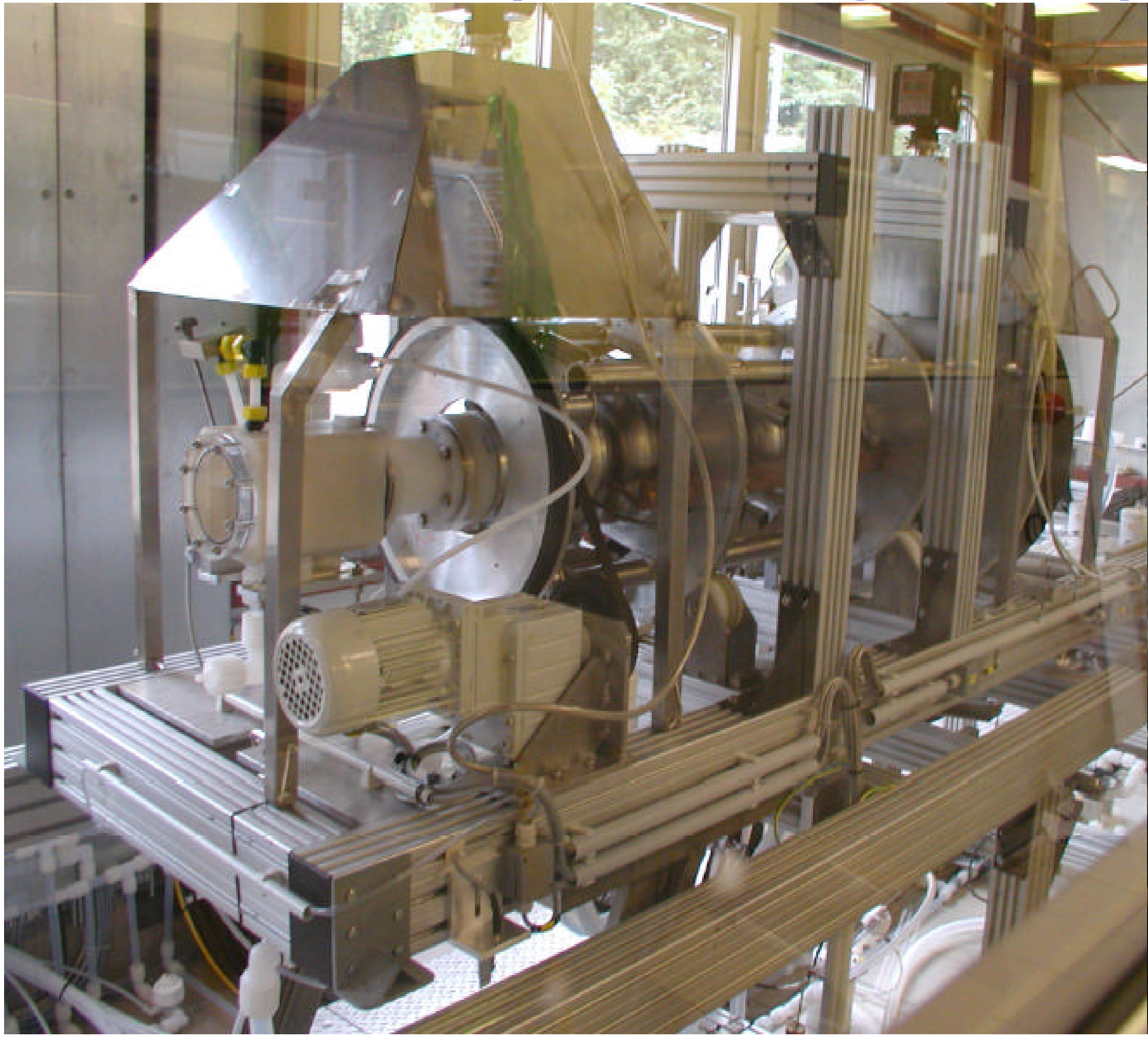


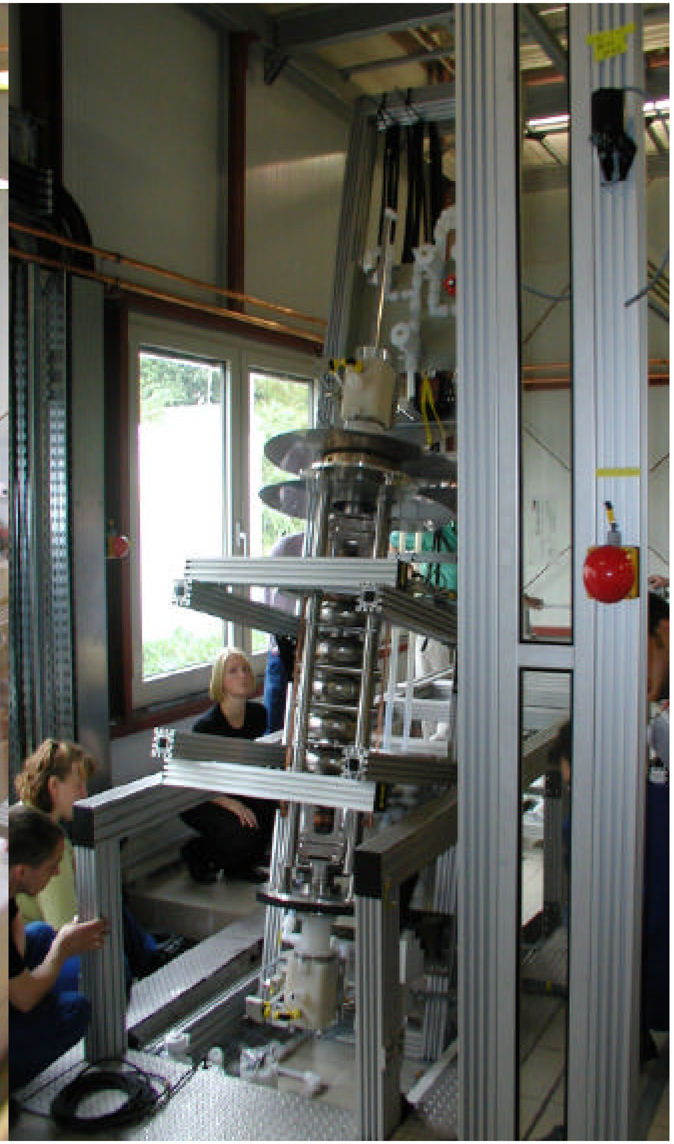
- Electropolishing is known since
  - 1912 (silver),
  - 1935 (copper)
  - 1970 (niobium cavities: Siemens)
- KEK and the company Nomura Plating have long experience with electropolishing (EP): e.g. Tristan cavities
- Nine-cells provided by DESY
- KEK and Nomura Plating performed the electropolishing process
- Final cleaning done at DESY

KEK-DESY Results on several EP Cavities

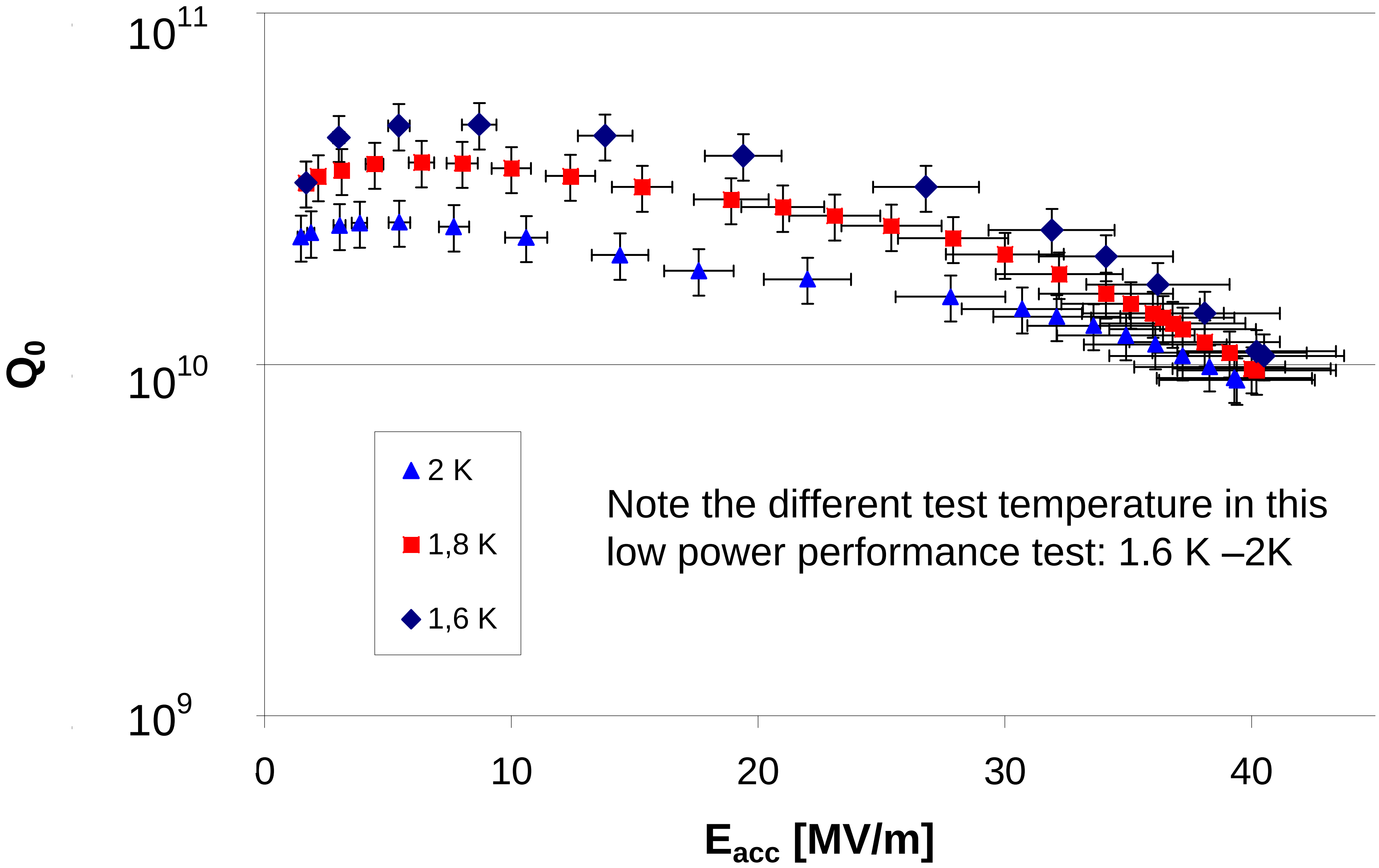


Electropolishing Setup at DESY

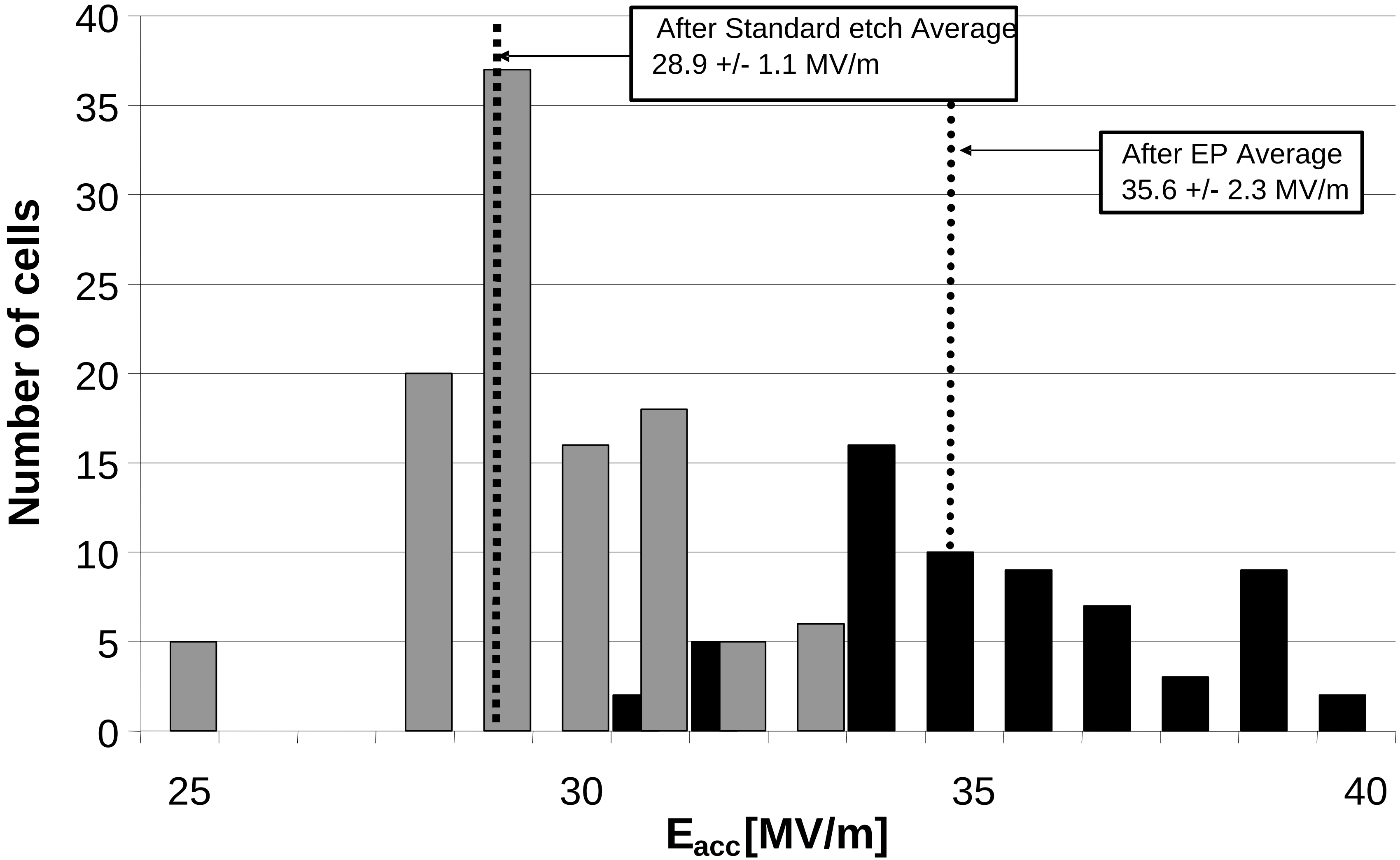




AC70: EP at DESY



Comparison of EP to Standard Etch



- EP offers systematically higher gradient than standard etch (single cell results from mode analysis of multi-cells)

Gradient Results for Different High Temperature Treatments:

Batch of cavities	800°C	1400°C	
single-cells	35.4 ± 5.3	34.7 ± 2.5	**MV/m**
nine-cells	34.0 ± 3.9	33.0 ± 3.3	**MV/m**
single cell analysis of nine-cell cavities	35.6 ± 2.8	35.6 ± 1.7	**MV/m**

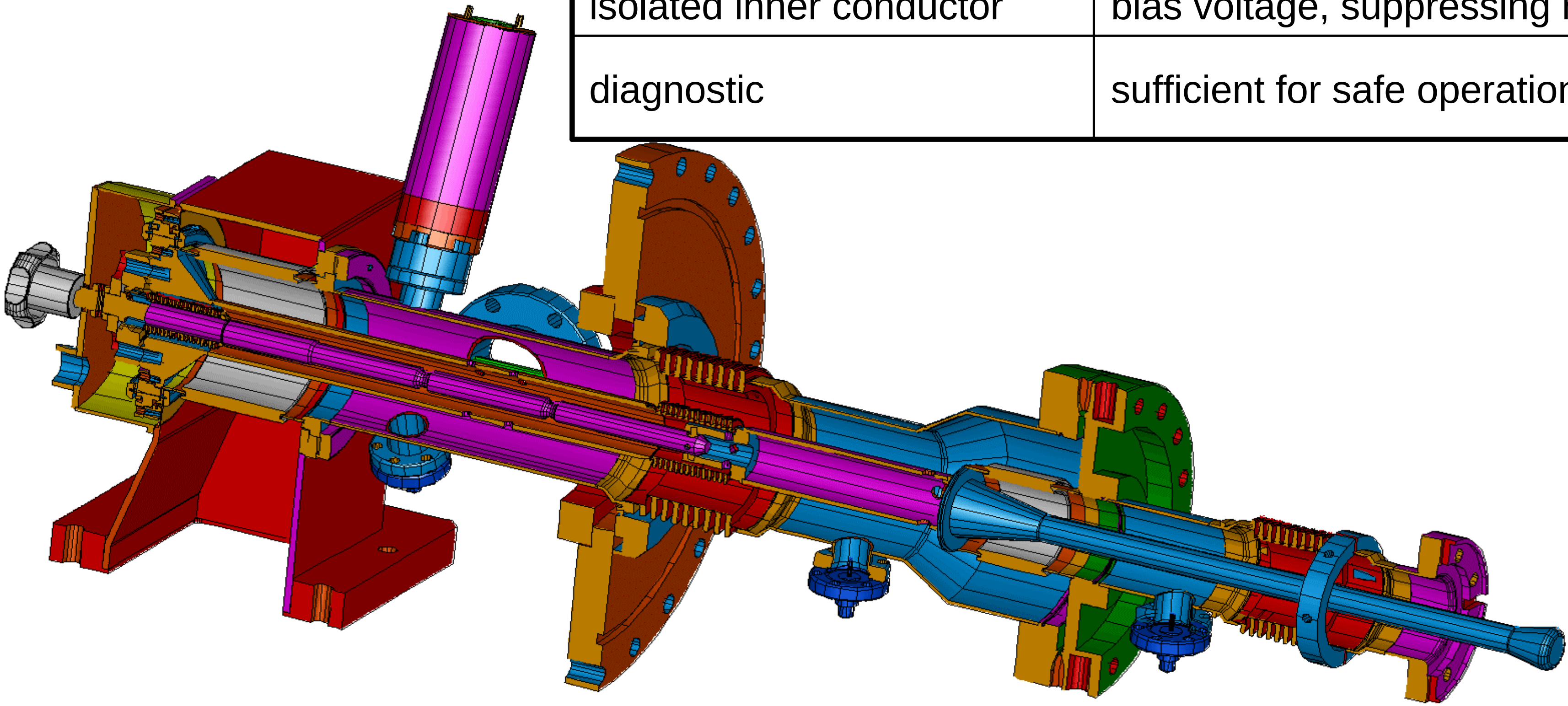
- Electropolishing opens up the possibility to avoid the time-consuming process of 1400°C firing (to increase thermal conductivity)
- Simplification of the cavity preparation and handling
- EP + 800°C will be the baseline preparation for the XFEL

Auxiliaries

- e.g. TTF-III coupler
- Active tuner

TTF III Coupler

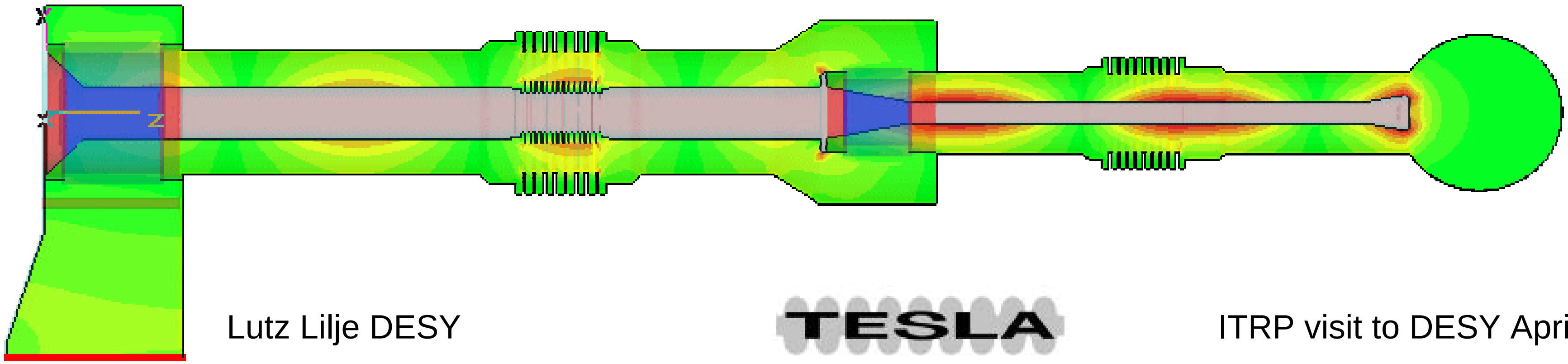
frequency	1.3 GHz
operation	pulsed: 500 µsec rise time, 800 µsec flat top with beam
two windows, TiN coated	• safe operation • clean cavity assembly for high Eacc
2 K heat load	0.06 W
4 K heat load	0.5 W
70 K heat load	6 W
isolated inner conductor	bias voltage, suppressing multipacting
diagnostic	sufficient for safe operation and monitoring



April 5th 2004

RF Specifications

	TTF	**TESLA** 9cell / upgrade	XFEL
Peak power + control margin	250 kW	250 kW / 500 kW	150 kW
Repetition rate	10 Hz	5 Hz	10 Hz
Average power	3.2 kW	3.2 kW / 6.4 kW	1.9 kW
Coupling (Qext)	adjustable (10^6 - 10^7)	fixed ($3*10^6$)	adjustable (10^6 - 10^7)



Coupler type		FNAL	TTF II	TTF III
cold part	window	conical	cyl.	cyl.
	coax diameter, mm	40	40	40
	Impedance, Ohm	50	70	70
bias		no	yes	yes
TiN coating		FermiLab	FermiLab	DESY
test stand TW	2Hz / 500µs	1MW	2MW	1MW
	2Hz / 1.3ms	1MW	1.8MW	1MW
	cold test done	yes	no	no
hiigh power test with Cavity	2Hz / <500µs	1MW	1MW	1MW
	5Hz/ 1.3ms SW	500 kW	500 kW	600 kW
	10Hz / 1.3ms	33MV/m	35MV/m	35MV/m
	cold test done	yes	yes	yes
fabricated total		16	20	62
assembled to		Mod.1*, 2	Mod.1*, 3*, 4	Mod.5, 6 (7, 8) SS
operated		1997-2004	1998-2004	2001-2004

Coupler Test Results

Coupler RF Specification			
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TTF III
cyl.
40
70
yes
DESY
1MW
1MW
no
1MW

hiigh powe test w Cavi	5Hz/ 1.3ms SW	500 kW	500 kW	600 kW
	10Hz / 1.3ms	33MV/m	35MV/m	35MV/m
	cold test done	yes	yes	yes

TTF III is a robust and reliable design:
significant margin in high power test

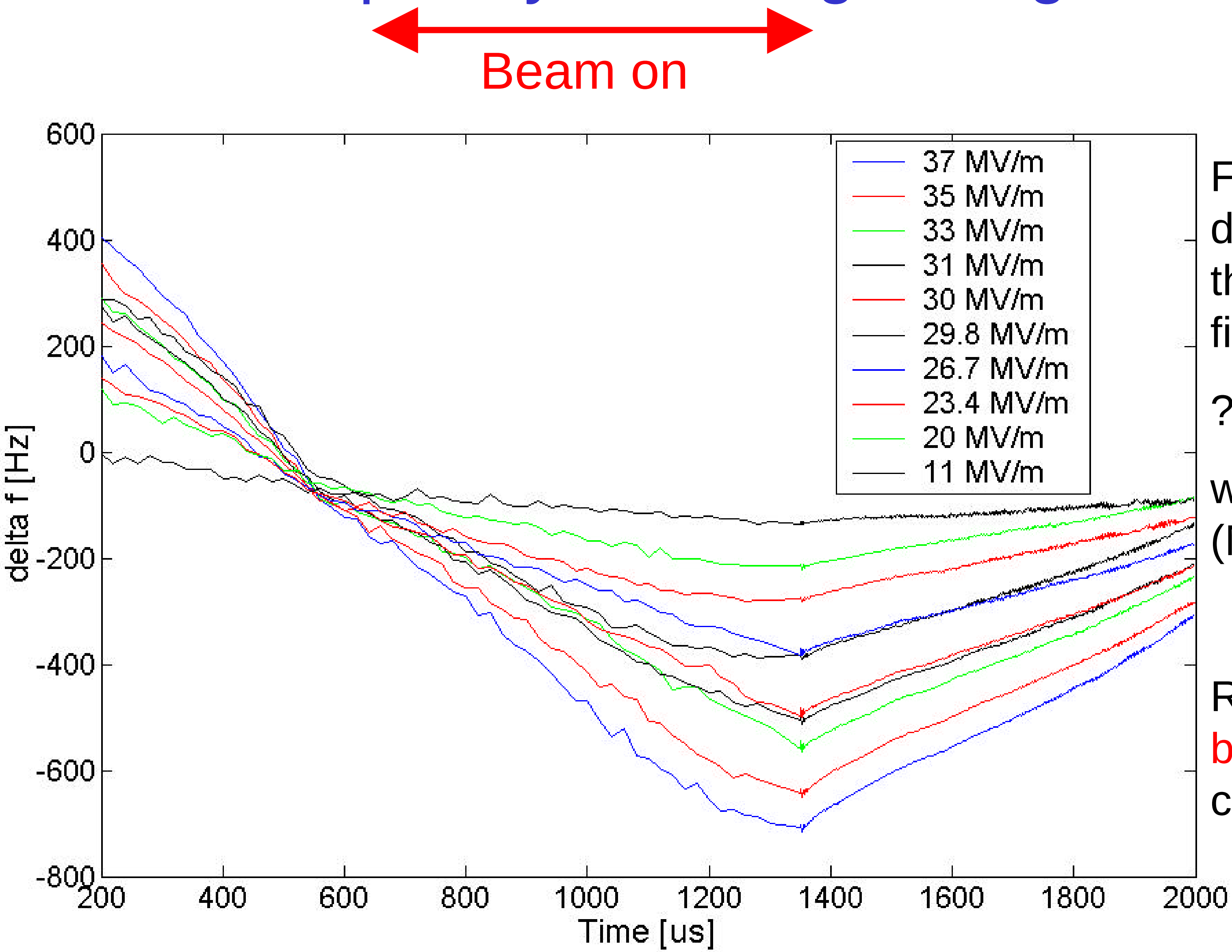
Active Tuner

- Lorentz force detunes the cavity during one RF pulse: If detuning is too large extra RF power would be needed

- Actively compensate the detuning of the cavity during the RF pulse by mechanical means

- Piezoelectric elements are suitable for this application (heavily used for fuel injection in car industry)

Frequency Detuning during RF Pulse



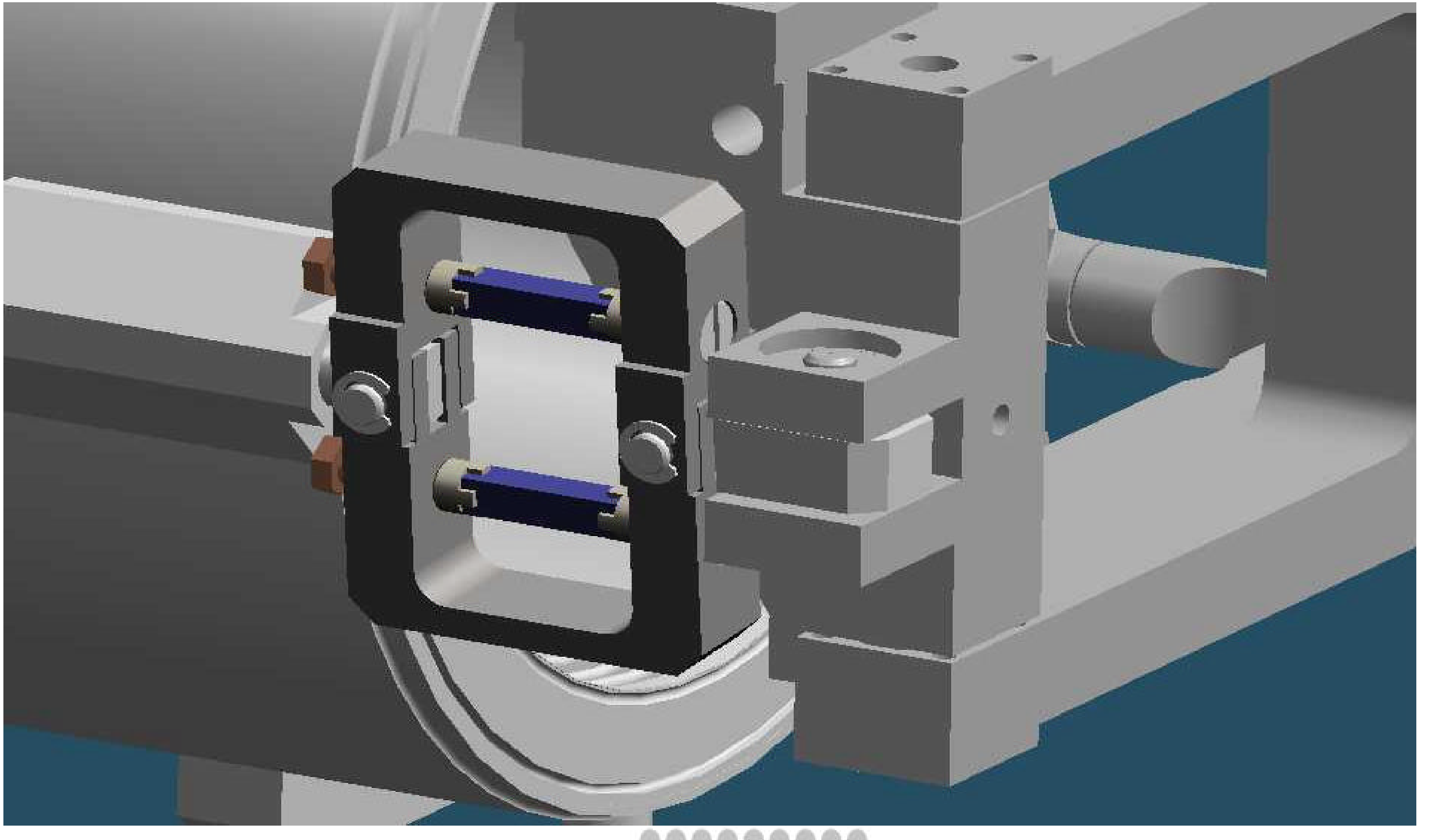
Frequency detuning due Lorentz forces of the electromagnetic field in the cavities:

?f = -K • E_{acc}^2

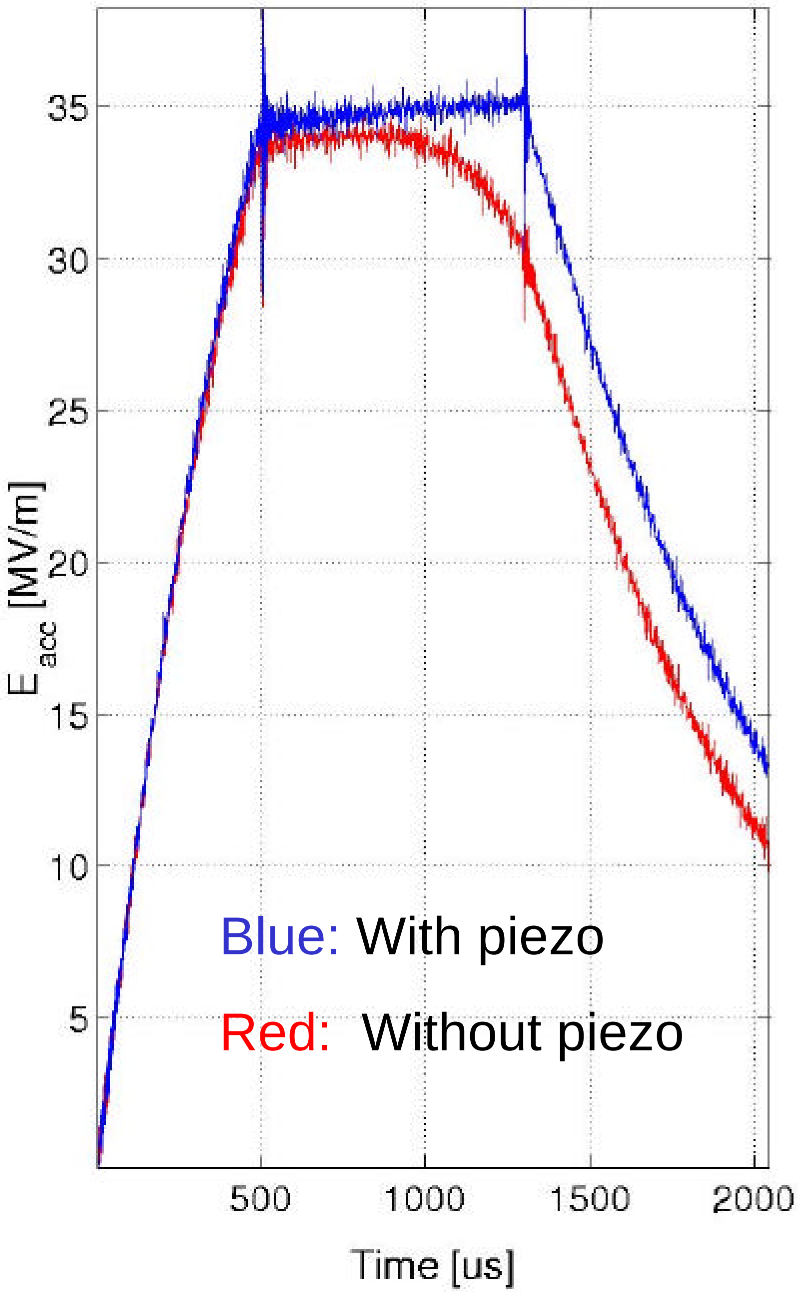
where K " 1 Hz / $(MV/m)^2$

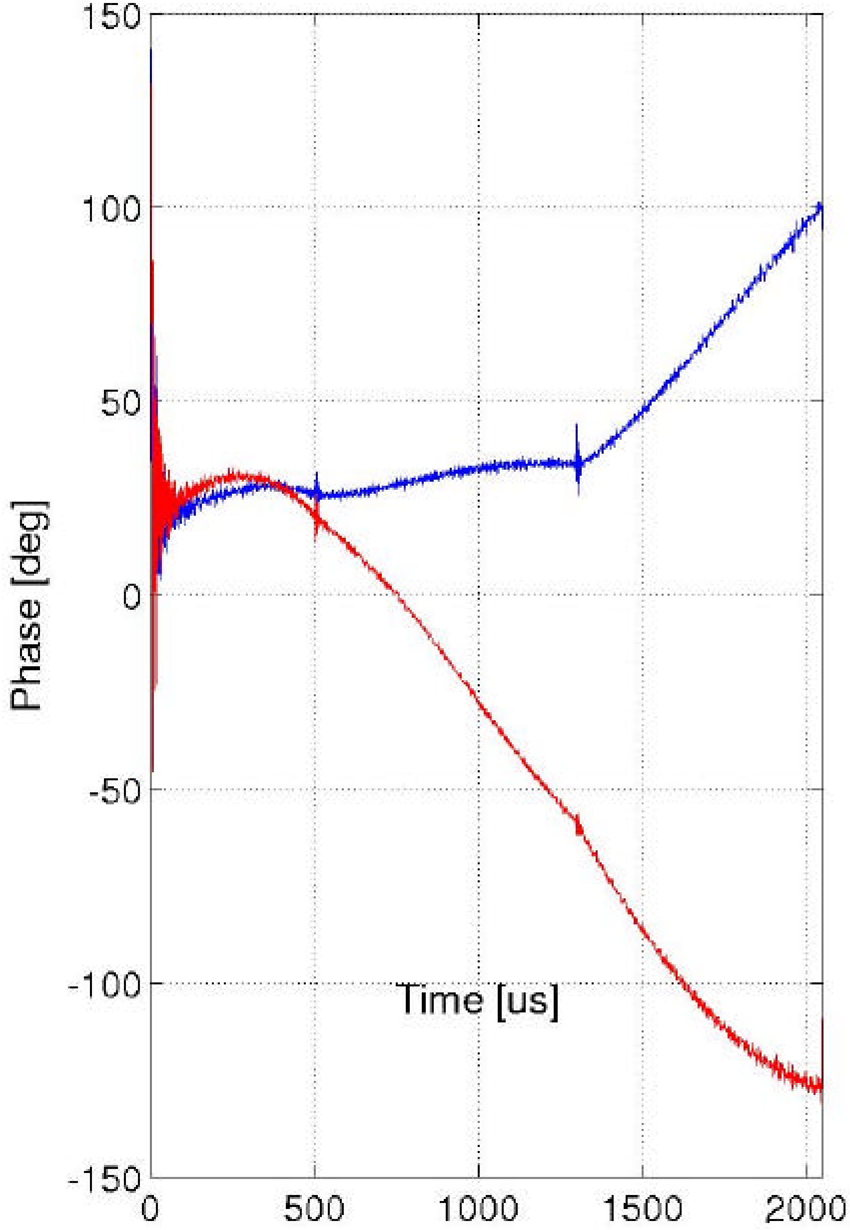
Remember: Cavity bandwidth with main coupler is " 300 Hz

Drawing of Piezoelectric Elements in the Tuning Mechanism



RF Signals at 35 MV/m





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R1 for TESLA-800

- Quote from ILC-TRC report:
  - "The Energy Working Group considers that a feasibility demonstration of the machine requires the proof of existence of the basic building blocks of the linacs. In the case of TESLA at 500 GeV, such demonstration requires in particular that s.c. cavities installed in a cryomodule be running at the design gradient of 23.8 MV/m. This has been practically demonstrated at TTF1 with cavities treated by chemical processing."
  - *TESLA-500 gradients have been proven now. See next talk.*
  - "The other critical elements of a linac unit (multibeam klystron, modulator and power distribution) already exist. "

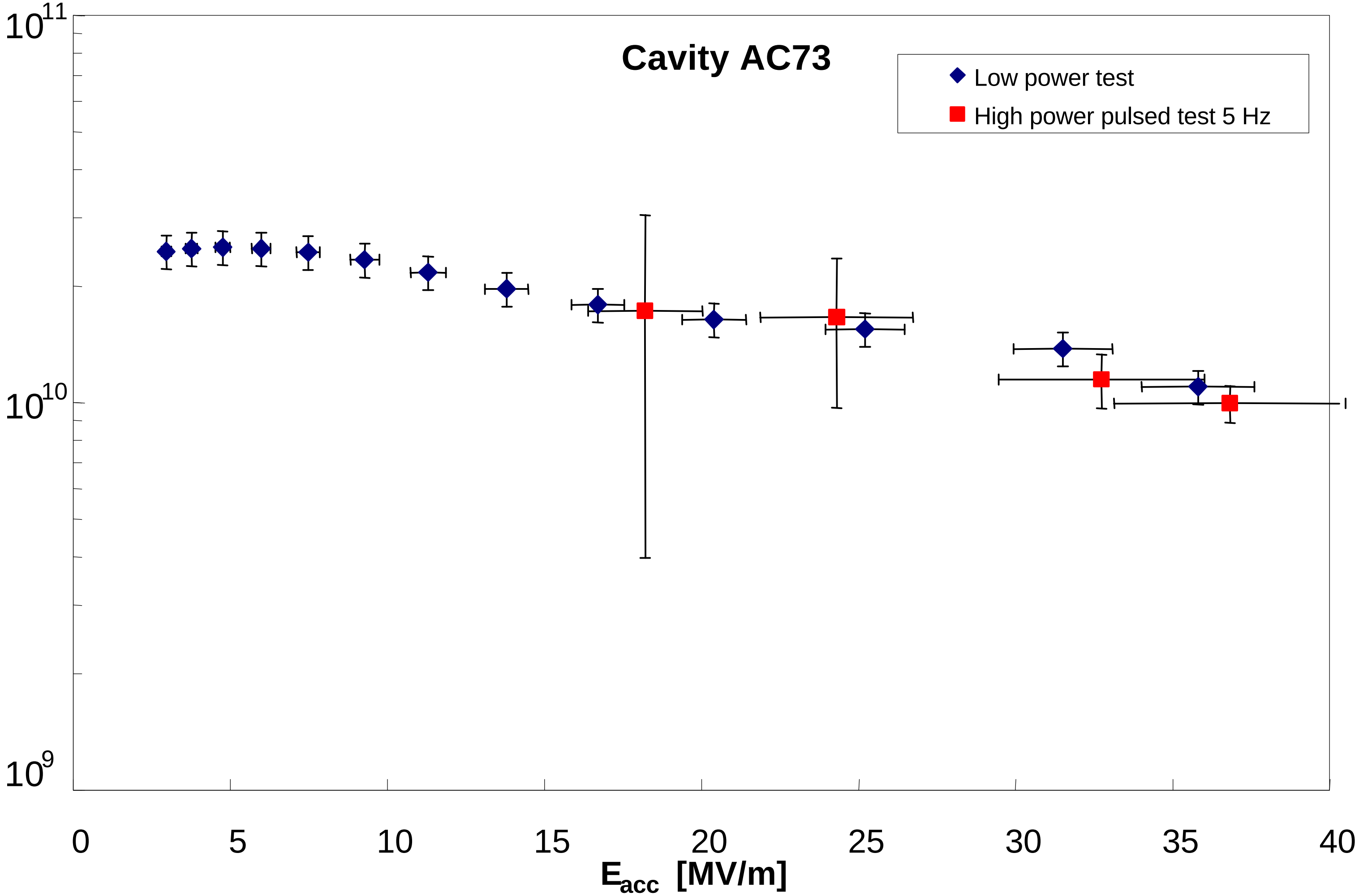
R1 for TESLA-800 (ctd.)

- “The feasibility demonstration of the TESLA energy upgrade to about 800GeV requires that a cryomodule be assembled and tested at the design gradient of 35 MV/m.
- The test should prove that quench rates and breakdowns, including couplers, are commensurate with the operational expectations.
- It should also show that dark currents at the design gradient are manageable, which means that several cavities should be assembled together in the cryomodule.
- Tests with electropolished cavities assembled in a cryomodule are foreseen in 2003.”

High-Power Test of Two EP Cavities in the TTF Horizontal Cryostat (CHECHIA)

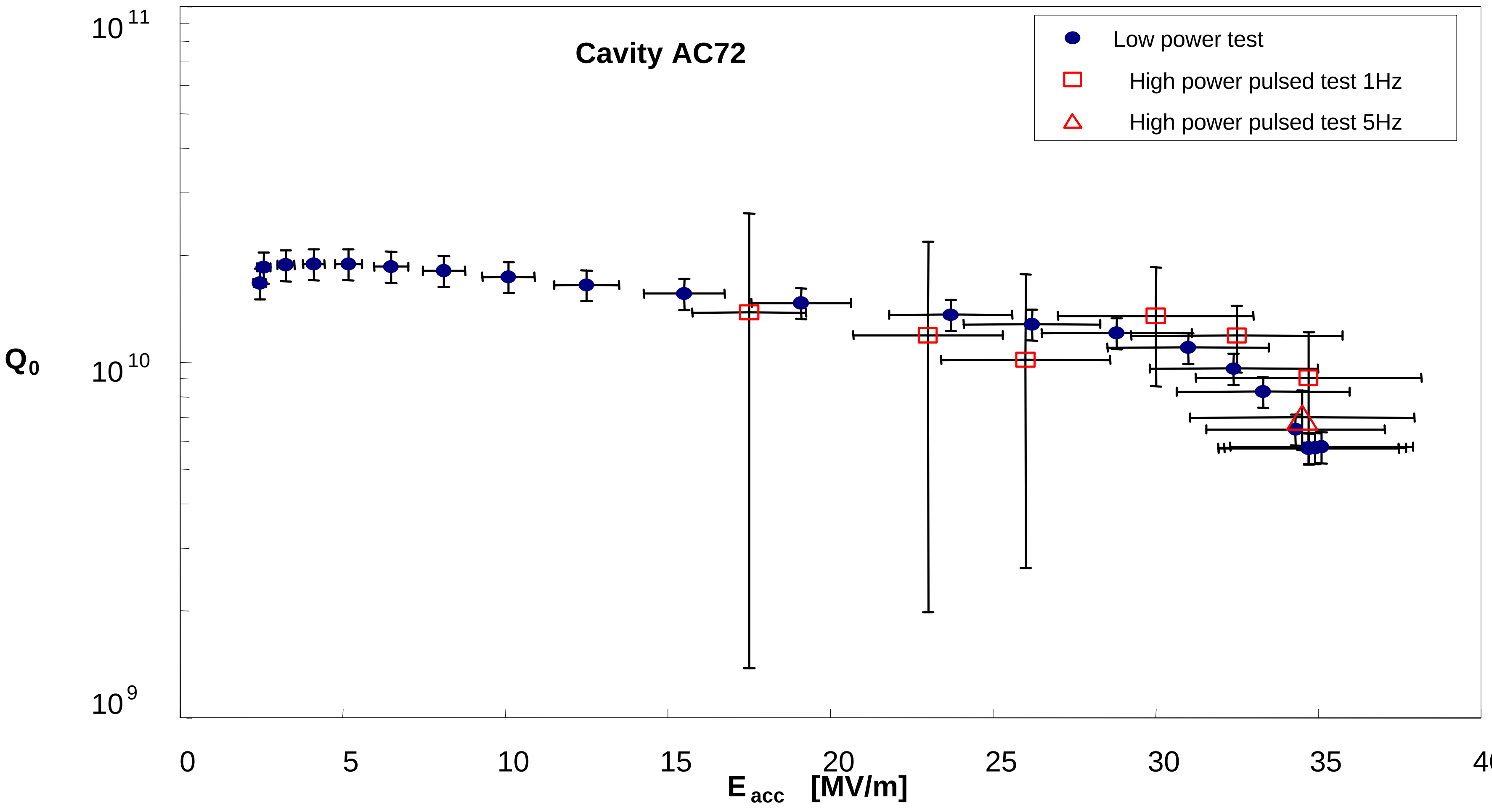
High Power Test Results

– No breakdown in 1100 hours at 35 MV/m (neither the Cavity nor the Coupler)
– No degradation was observed when breakdowns were forced (thermal quenches and coupler breakdowns)
– Standard X-ray radiation measurement indicates that both tested cavities are radiation-free up to 34 and 35 MV/m respectively
– Dark current behaviour can be checked directly in the high power test setup, but the setup needs a modification, which is underway



High Power Test Results

- Conclusion:
  - Horizontal high power tests give Cavity-Coupler-wise the full information about the system's behaviour.
  - These tests will be continued as the cavities are prepared to get more statistics. A high gradient module will be built.

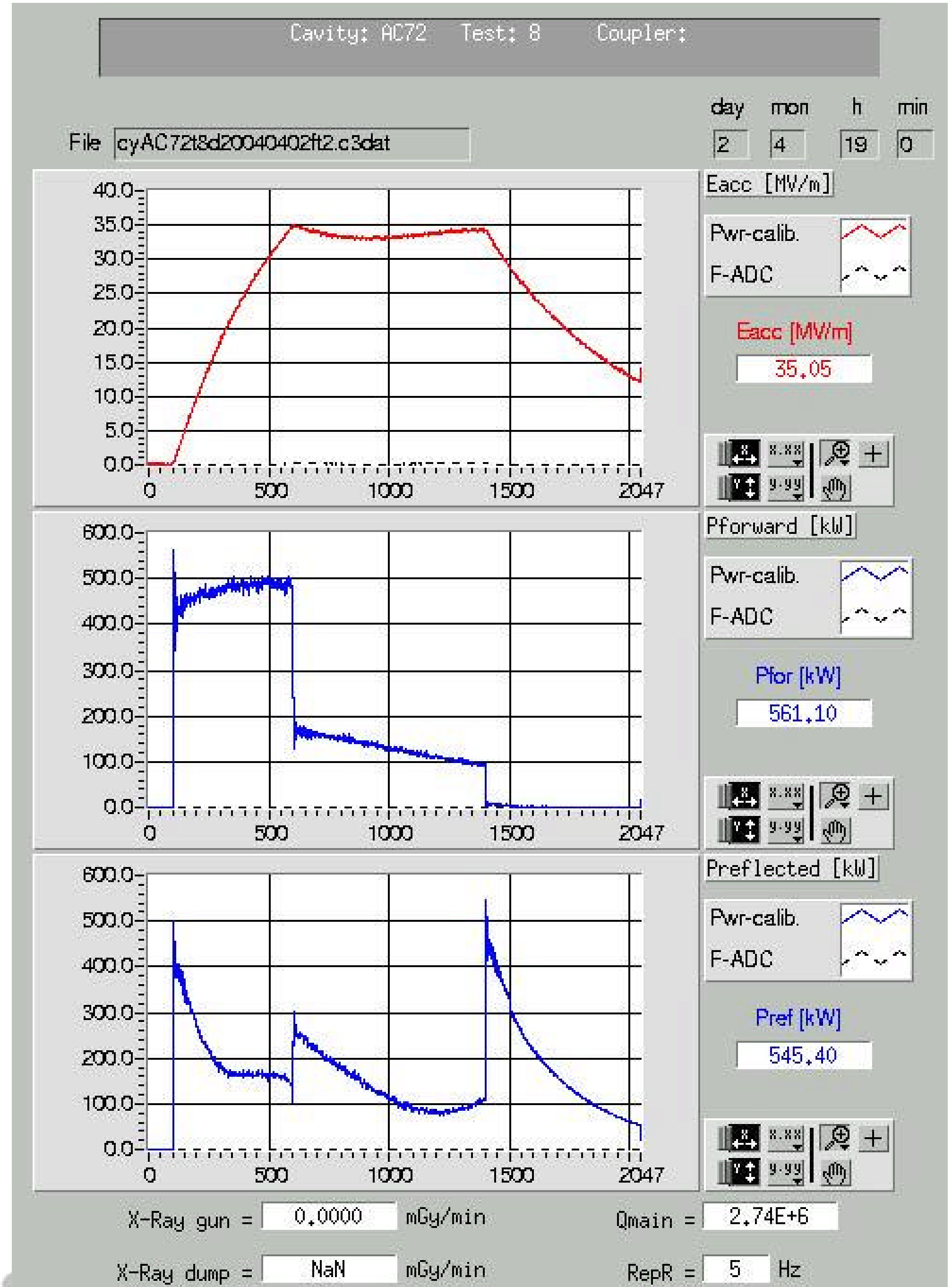


Cavity Test Inside a Module

Cavity Test Inside a Module

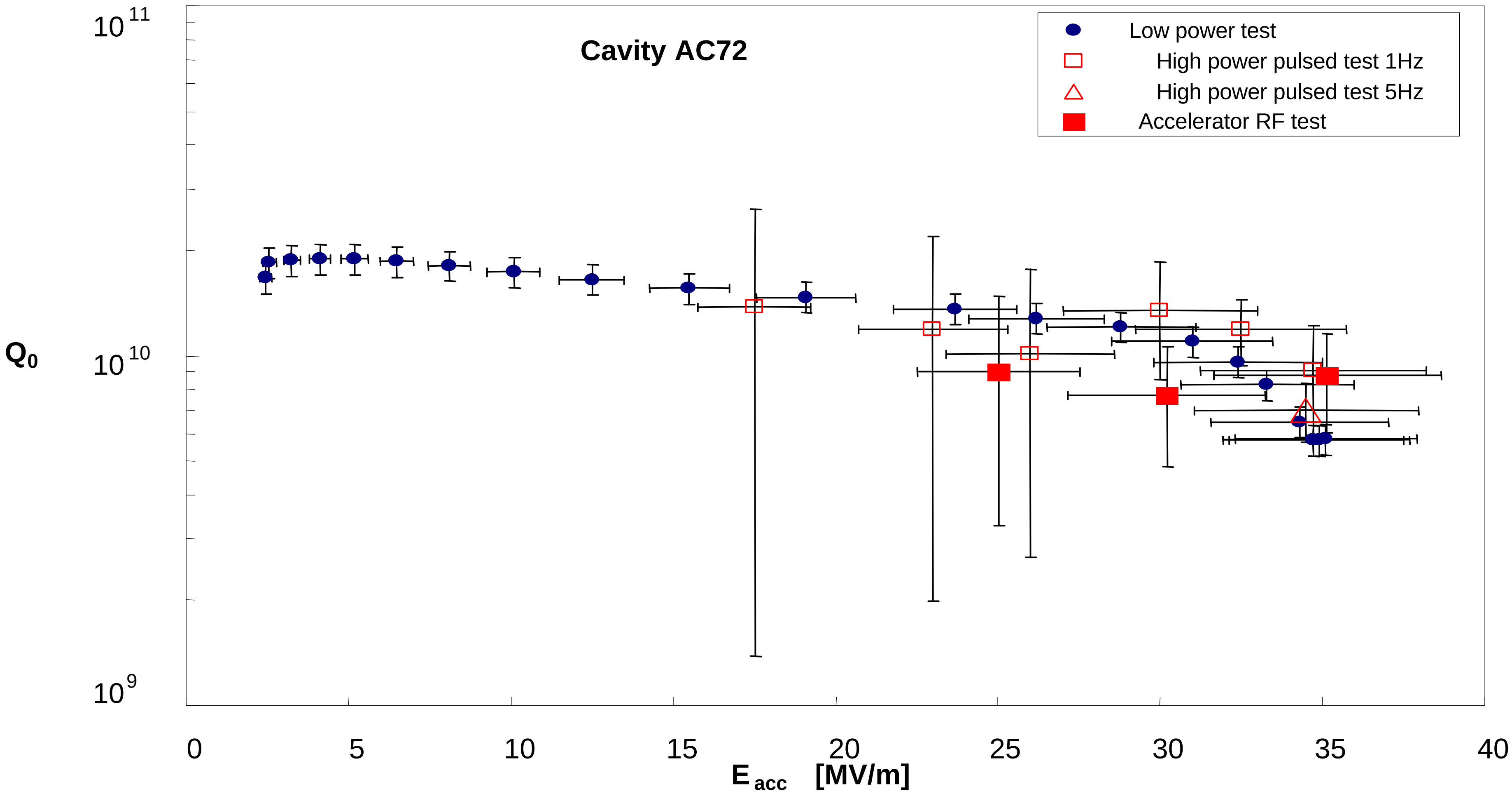
- One of the high power tested cavities (AC72) was installed into an accelerating module for the VUV-FEL
- Cooldown of the LINAC finished a week ago
- Cavity was individually tested in the accelerator with high power RF
- Result:

  35 MV/m in the accelerator!



Cavity Test Inside a Module (ctd.)

- Testing has just begun
  - Standard X-ray radiation measurement indicates no radiation-free up to 35 MV/m
  - LLRF has been operational at 30 MV/m
  - Active compensation of Lorentz-force detuning is being setup



Summary

- Several electropolished nine-cell cavities have shown gradients of 35 MV/m and higher. Some of these have been prepared without 1400°C firing thus potentially simplifying the cavity preparation procedures.
- Electropolishing will be the method of surface preparation for the XFEL.
- 35 MV/m have been achieved in a high power test of TESLA cavities fulfilling the R1 requirement for breakdowns and quenches.
- No degradation has been observed in neither the cavity nor the coupler as is expected for superconducting cavities.
- Couplers have been operated at nominal power levels for extended periods of time including TESLA-800 parameters. Couplers sustained significantly higher power levels in test stands.
- Active compensation of the frequency detuning during the RF pulse (Lorentz-force detuning) has been demonstrated.
- 35 MV/m have been reached in a cavity inside an accelerator module.
- The module test stand is expected to become available in 2005.

References

- R. Brinkmann, K. Flöttmann, J. Rossbach, P. Schmüser, N. Walker, and H. Weise, editors, TESLA - Technical Design Report, volume II, DESY, March 2001, DESY 2001-011, ECFA 2001-209, TESLA Report 2001-23.
- K. Saito et al., Superiority of Electropolishing over Chemical Polishing on High Gradients, In Proceedings of the 8th Workshop on RF Superconductivity, pp. 759 – 813.
- K. Saito et al., High Gradient Performance by Electropolishing with 1300 MHz Single and Multi-cell Niobium Superconducting Cavities, In Proceedings of the 9th Workshop on RF Superconductivity, pp. 288–291.
- P. Schmüser et al.; The Superconducting TESLA Cavities; PRST-AB 3 (9) 092001
- B. Visentin, J. Charrier, B. Coadou, and D. Roudier, Cavity baking: A cure for the high accelerator field Q0 drop, In Proceedings of the 9th Workshop on RF Superconductivity.
- L. Lilje, P. Schmüser, et al.; Improved surface treatment of the superconducting TESLA cavities; Nucl. Inst. Meth. A 516 (2-3); 2004; pp. 213-227.
- L. Lilje, E. Kako, K. Saito, P. Schmüser, et al.; Achievement of 35 MV/m in the Superconducting Nine-Cell Cavities for TESLA; 2004; published in NIM A; DOI: 10.1016/j.nima.2004.01.045